Eingereicht als Tagungsbeitrag zum "21st International Congress of Refrigeration"
Washington, 17. bis 22. August 2003 (Veranstalter IIR/IIF), Paper ICR0641

SMALL-CAPACITY WATER/LIBR ABSORPTION CHILLER FOR SOLAR COOLING AND WASTE-HEAT DRIVEN COOLING

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ABSTRACT

Recently a growing demand for small scale absorption chillers for both solar cooling and trigeneration, i.e. utilization of cogenerated heat for cooling, has been encountered. Up to now, chillers below 35 kW are not available. Following up a joint European project, a prototype development of a 10 kW absorption chiller with water/lithiumbromide as working fluid has been initiated by a German producer and distributor of solar thermal systems. The plant uses driving hot water of usually 56 to 85°C for solar and 80 up to 105°C for trigeneration application respectively and exhibits a considerable improvement in performance as compared to present plants. By means of a careful cycle design and a fully automated control an efficient part load behavior down to 40% load will be achieved.

With the aim of an optimum configuration and control of the system a transient system simulation has been carried out. Operational data gathered during the start-up phase will be presented. Further testing under realistic conditions with solar collectors as driving heat source will be carried out in a solar cooling installation of an office building in Berlin. A field-test is under preparation.

Key words: sorption chiller, solar cooling, trigeneration, cycle analysis, heat exchanger design, prototype, test, transient simulation

INTRODUCTION

The present market increase of compressor air-conditioning appliances in Europe, especially in hot and humid areas like the Mediterranean countries, results in a growing electricity demand. Solar cooling using sorption technology offers the prospect of air conditioning systems with drastically reduced electricity consumption. The lack of respective systems on the market has led to the development of a low-temperature driven 10 kW water/lithiumbromide absorption chiller, using as heat source hot water from about 56°C to 105°C according to the possible cooling load range and chilled water temperature range. A first prototype has been developed by ZAE Bayern. It has been tested by both ZAE Bayern and the french project partner Costic in 2001 (Michel *et al*., 2001). A follow-up cooperation project together with ZAE Bayern, Technical University of Berlin, Institute for Rehabilitation and Modernization of Buildings (IEMB) and Phönix Sonnenwärme AG has started in September 2002. Within the follow-up project a second, specially adapted and improved prototype will be built, installed in a solar thermal system and experimentally tested under realistic operating conditions, using the cold provided for the air conditioning of office rooms. A third prototype simultaneously will undergo laboratory tests at the Technical

University of Berlin. Key research aspects under investigation are the performance of chiller and solarthermal loop in full and partial load, finding an optimum techno-economic system configuration and developing a simple control algorithm. The project aim is to optimise the prototype and the solarthermal system with regard to these aspects, allowing field demonstration to start after soon. As each solar cooling system is different - even when using the same chiller - a simulation is a prerequisite to design field test installations as well as commercial applications. Therefore, a transient simulation of the whole solar cooling system has been carried out to gain information for the test stand design.

1 CHILLER DESIGN

For installation in small scale air-conditioning applications compact sorption chillers for operation with low-grade heat are required. An optimised part-load operation and an efficient control scheme have been identified as major aspects of the project. With respect to the low cooling capacity a single-stage process allowing for both a straight-forward plant design and a reliable and durable plant operation was chosen. For that reason, advanced cycle concepts as described by Schweigler *et al.* (1996), Ziegler *et al.* (2000), and Pietsch and Wobst (2001) suitable for enhanced low grade-heat utilization, have not been taken into account.

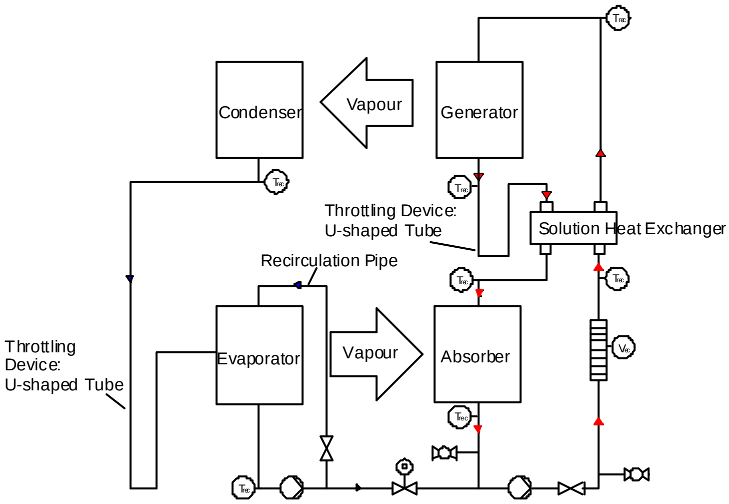

Figure 1: Process scheme of the single-stage cycle.

In contrast to commercial chillers of the type WFC, manufactured by Yazaki Co., for circulating the LiBr solution a hermetic centrifugal pump with speed control and a second hermetic pump for recirculating the refrigerant is used. This ensures an efficient and reliable part-load operation with minimized solution circulation and thus an optimisation of the part-load COP. Figure 1 shows the realized single-effect process scheme.

1.1 Heat Exchanger Design

For an efficient coupling of the chiller to a low temperature heat source, such as solar collectors or cogeneration engines, a careful heat exchanger design mainly for the generator and absorber is required. In contrast to applications with a high temperature driving heat source where pool boiling is applied in the solution regenerator, for low grade heat utilization a falling film design with counter-current flow of heat carrier and refrigerant solution has to be established. In contrast to pool boiling, falling film heat exchangers have the advantage of overlapping internal and external temperatures in counterflow arrangement, leading to lower return temperatures of the driving hot water. In addition, the falling film design requires less solution inventory. Yet, additional effort is imposed by the solution distribution system which serves for wetting the falling film heat exchanger.

The detailed design of the falling film heat exchangers involves several technical criteria, such as the interdependence of pressure drop and heat transfer coefficients. An optimum design has been worked out by adjusting the number of external water passes and the tube bundle height. The variation of the tube bundle height n_H

serves to match the required wetting of the heat exchanger tubes for a given specific solution circulation f, which is the ratio of the dilute solution mass flow to the refrigerant mass flow. A low solution circulation enables a higher COP of the chiller due to reduced losses of the solution heat exchanger and is therefore desirable.

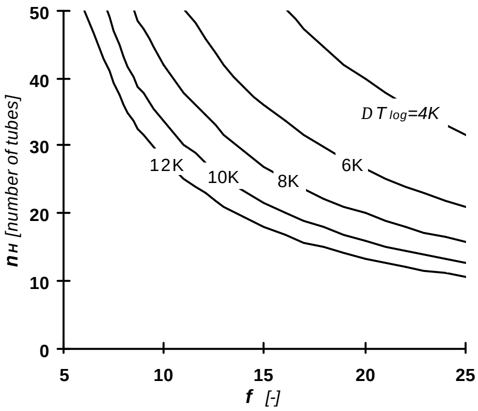

Figure 2: Required tube bundle height n_H [number of tubes] as a function of the specific solution circulation f [-] with parameter driving temperature difference ?T_{log} [K]

Figure 2 shows the required height of the tube bundle n_H as a function of the specific solution circulation f for different values of the driving temperature difference ?T_{log}. With decreasing driving temperature difference and decreasing solution circulation the height of the tube bundle has to be increased. Under the given restrictions of rather low driving temperature differences the shape of the rather narrow and tall tube bundles and their compact housing becomes the main issue of the plant design.

1.2 Plant Layout

Table 1: Dimensions and operational data of second prototype

Working pair:	Water/LiBr	
Part load capability:	40% –160%	
COP:	0.74	
Evaporator:	cooling capacity	10 kW
	chilled water in/out	18/15°C
	flow rate	2.9 m^3/h
Generator:	driving heat	13,5 kW
	hot water in/out	85/75°C
	flow rate	1.2 m^3/h
Absorber/Condenser:	reject heat	23 kW
	cooling water in/out	27/35°C
	flow rate	2.6 m^3/h
Dimensions:	Length	0.8 m
	Width	0.4 m
	Height	1.8 m
Mass:	approx. 400 kg	

Figure 3: 10 kW absorption chiller during start-up at ZAE Bayern (first prototype).

Table 1 summarizes technical data of the second prototype for 100% load (10kW cooling capacity). The specified part load capability is related to constant flow rates of the external heat carriers, a constant cooling water inlet temperature of 27°C and a constant chilled water outlet temperature of 15°C. The chilled water is used to operate chilled ceilings which demand 15°C inlet temperature and return the water at up to 18°C. An important benefit of a high chilled water temperature for the system – e.g., compared to standard conditions in Germany (6°C/12°C) - is a lower required hot water temperature and therefore a higher efficiency of the solarthermal system. With fixed chilled water and cooling water conditions (flow, temperature) and a constant hot water flow the cooling capacity, or load respectively, is determined by the hot water inlet temperature which varies from 56°C (40% load) to 105°C (160% load).

Rectangular vessels have been chosen as housing for the main components evaporator/absorber and generator/condenser. In analogy to large capacity standard plants low and high pressure components have been mounted on top of each other. Underneath the main vessels a compact solution heat exchanger and the solution and refrigerant pump are located. To ensure a reliable unattended operation a compact control unit has been developed which coordinates the start-up and stop routine, respectively. An integrated cycle guard function surveys internal process parameters in order to avoid crystallisation or freezing and detects upcoming vacuum problems. A view of the first prototype of the 10 kW chiller is given in Figure 3.

1.3 Operation Results

After design, manufacturing and start-up the first prototype plant has been tested in a solar cooling installation. During the start-up phase at ZAE Bayern a general test of the plant performance has been carried out. A test protocol for full load operation is shown in Figure 4. The left plot presents in three repetitions the heat fluxes of all external heat carriers during the operational phases start-up, stationary operation, shut-down while the corresponding temperatures of the external heat carriers are shown in the right plot. The designed chilled water capacity of 10 kW in stationary full load has been realised with a COP=0,77 for the external heat carrier temperatures as specified for the first prototype.

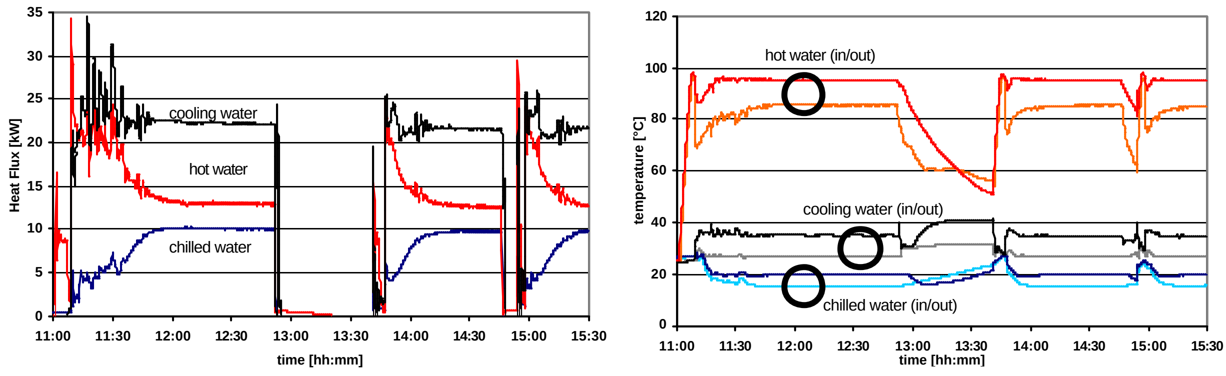

Figure 4: Test protocol for full load operation of prototype 1.
Hot water, cooling water and chilled water capacity (left figure) and external heat carrier temperatures (right figure).

For the oral presentation a test protocol of the second prototype, specially designed for the modified operational conditions shown in table 1, will be available.

2 SYSTEM INTEGRATION

Integrating an absorption chiller in a solarthermal system requires careful system design under both energetic and economic aspects. From an energetic point of view, a solar fraction as high as possible is desirable, delivering maximum primary energy savings over the year. Nevertheless, the energetic optimum will most likely not be the economic optimum. A large collector field for example will deliver a high solar fraction, but increase the cost dramatically. Therefore, based on user-demanded cooling load, building conditions and operating hours per year, a well balanced system with adequate solar fraction, stable performance and low investment cost needs to be found.

Choosing the right component sizes and dimensions and developing a sufficient control strategy are crucial factors for achieving this task. The components which mainly determine the performance of the whole system are collector and storage tank as well as the solar loop heat exchanger, cooling tower and the auxiliary heater. An option towards an economically optimized system is the application of free cooling, i.e. using cooling water from the cooling tower directly for the chilled ceiling panels without absorption chiller operation, whenever the outside wetbulb temperature is sufficiently low. At present, the benefit of free cooling has not been investigated.

2.1 System design and its transient simulation

The chiller is being integrated in a typical solar installation of an office building in Berlin, Germany, with 150 m^2 room area and an internal cooling load of 4 kW. The windows are oriented south west and have an area of 43 m². This leads to air temperatures up to 33°C without air conditioning. Figure 5 displays a system overview.

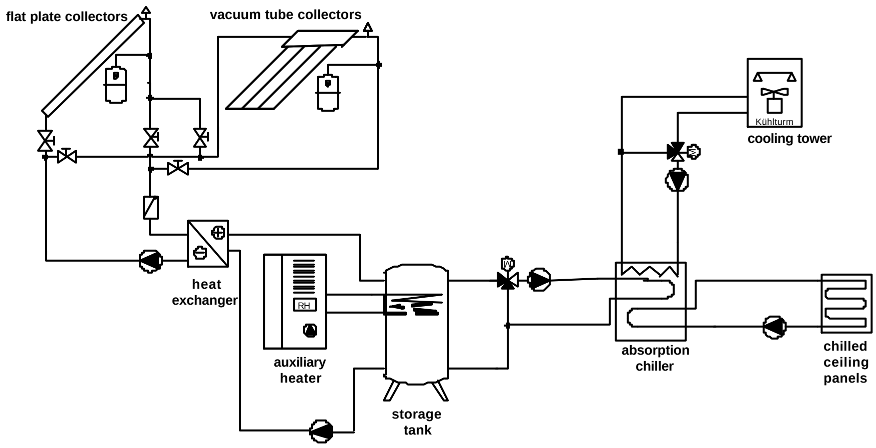

Figure 5: Schematic of the solar cooling system

The solarthermal part of the system consists of a 42 m^2 flat plate collector field and a 22 m^2 evacuated tube collector field, both being installed on the flat roof of the office building. They can alternatively be connected to the heat exchanger and each one is sufficient in thermal power to run the chiller independently. Although two types of collectors mean higher costs for the test stand they allow to gain more information about thermal behaviour, temperature level and specific system capacity. A 750 litre storage tank serves as a buffer for hot water but can be bypassed. Pumps with variable rotation speed are being used in the collector and the storage loop, whereas in the generator, cooling tower and chilled ceiling loop constant speed pumps are being used to allow temperature control. An external plate heat exchanger separates the antifreeze glycol/water mixture of the solar loop from the storage water. An auxiliary 28 kW LPG condensing boiler has been installed for the sake of better experimentation, but should be avoided in commercial installations. The cooling water for the 10 kW water/LiBr absorption chiller is provided by a wet cooling tower of 23 kW capacity. Chilled ceiling panels consisting of aluminium-finned copper tubes are being used to distribute the chilled water of the absorption chiller through the office rooms. The whole system is being installed at the moment and will start operation in early summer 2003.

To allow a straight forward control algorithm and to lower the risk of malfunction or failure the number of controlled components should generally be kept low. In the test stand two continuously variable three-way mixing valves have been installed to control the supply temperature of hot and cooling water for the chiller, thereby providing the necessary control on the cooling capacity. Performance control of the chiller can also be reached via a combination of mass flow and temperature control of the external heat carriers but is limited due to reduced overall heat transfer coefficients of the chiller at lower flow speeds. The control strategy for the test stand is a combination of an on-off- and P-control in the solar and storage loop and a PI-control for the external heat carriers of the chiller: The solar pump starts operating with a 30% part load mass flow if solar insolation exceeds 200 W/m^2, reaching maximum mass flow at 700 W/m^2. The pump of the storage loop operates if the inlet temperature on the solar side of the heat exchanger is, e.g., 10 K higher than the top temperature of the storage. The generator loop pump is being switched on when the top temperature of the storage exceeds the set point for the minimum operating temperature of the chiller of, e.g., 2K and is switched off when the top temperature of the storage falls below, e.g., 65°C. The outlet temperature of chilled water is supplied at 15°C by controlling the three way mixing valve in the generator loop. The three way valve in the cooling water loop is used to control the supply temperatures of the cooling water, ensuring chiller operation within safe temperature limits, but could be replaced by a controlled cooling tower fan.

Each solar cooling system is different even if the same chiller is being used. Thus an off-the-shelf design as known from solar heating applications is not advisable for solar cooling. In contrast to heating applications, where the warm water demand is the only criterion, the demand on a solar cooling installation is depending on both system and building factors. System factors are component data, e.g. collector field and storage tank size; building factors are building insulation and orientation, external shading, climatic conditions, internal loads etc. It is therefore advisable to perform a thorough simulation ahead of planning such a system to prevent unnecessary high investment cost and guarantee the later operation according to user-based demand. Such a transient simulation has been performed using the TRNSYS software developed by the Solar Energy Laboratory of the University of Wisconsin (Klein *et al*., 1998). The simulation deck consists of the main components of the solar air-conditioning system plus a model for the thermal building load, controllers and interconnecting piping. A new TRNSYS type has been developed for the absorption chiller which uses the method of characteristic equations for absorption chillers as described in Ziegler *et al*. (1999). The model is kept less complex as described in Albers (2002) since the non linear part load behaviour as shown in York (2002) is avoided by the recent chiller design. The thermal building load of the office building was modelled using the TRNSYS type 56 and the PREBID software. Since test reference year (TRY) weather data are only available in hourly resolution, original weather data from Berlin in 2002 with a 10 minute time step resolution have been used. The simulation circuit diagram can be seen in Figure 6, showing the information flow and TRNSYS types being used.

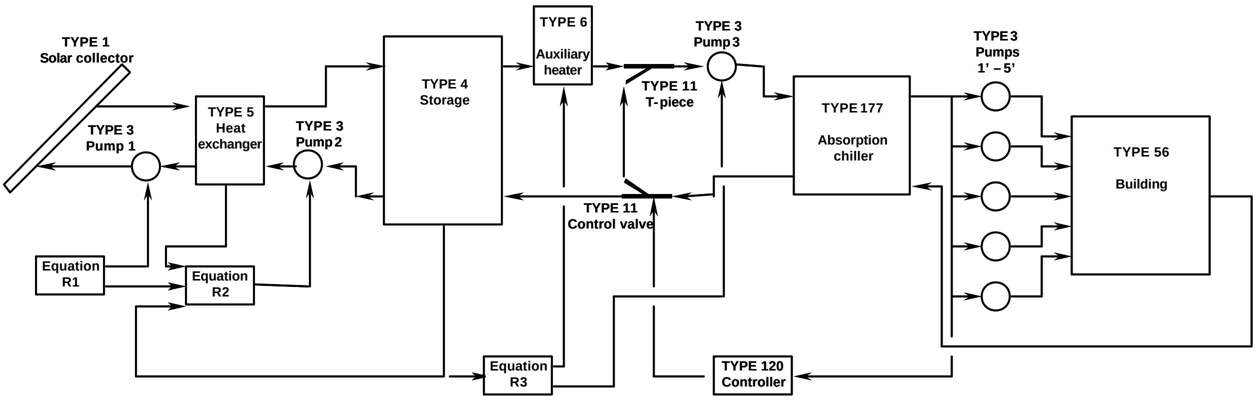

Figure 6: Circuit diagram and TRNSYS types used for modelling the system

2.2 Simulation results

A parameter study has been performed in order to find the influence of the various components on the overall system performance of the test stand system. Collector field and type as well as storage tank size have been varied taking into account both energetic and user-oriented criteria. The usable heat gain for the chiller, i.e. heat gain above 65 °C, serves as an energetic criteria. The user aspect, i.e. the discomfort is expressed by the number of hours per year in which the required room temperature (German Industry Norm DIN 1946, 1994) is exceeded (abbreviated EH, Exceeding Hours). For the parameter variations of collector field and storage tank size the auxiliary heater was out of operation. Figure 7 shows the variation of the solar gain and the number of exceeding hours, EH, as a function of the collector field size and type. As expected, a larger collector field results in a lower number of EH, which is due to a higher solar gain and therefore a higher cooling load coverage.

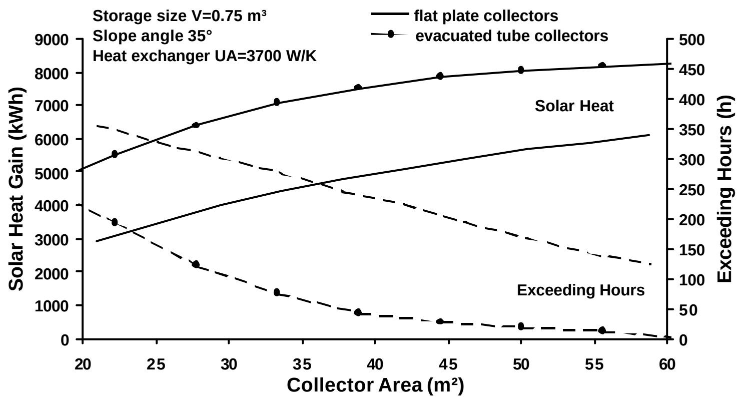

Figure 7: Variations of collector field type and area

Considering the aspect of user-comfort, the collector field of the system presented should thus be as large as possible with mainly economical limits. For the test stand system (as in most other applications), the collector field size was limited by the available roof area and has been chosen accordingly. Both collector fields can be partially deactivated though, allowing 75% and 50% part load operation. The storage tank size was found to be of little influence on the number of EH. This demonstrates that a large buffer volume is not needed for the system presented which in turn shows the simultaneousness of thermal building load and solar supply. Theoretically the storage tank could be replaced with a hydraulic junction. To allow sufficient experimental validation of the simulation results, both, a storage tank with a volume of 750 litres and a storage bypass has been chosen for the setup presented.

3 SUMMARY

A compact absorption chiller with the working pair water/LiBr and a cooling capacity of 10 kW has been developed for solar cooling applications. The plant has been designed for driving hot water temperatures in the range of 60 to 80°C. The chiller itself can also be operated with driving temperatures of 80 to 100°C and adapted cooling capacity, thus matching the conditions of small scale trigeneration systems. In analogy to large capacity chillers falling film heat exchangers in rectangular vessels have been applied.

During the start-up phase at ZAE Bayern the desired performance data, i.e. 10 kW chilled water capacity with COP > 0,75, have been realised. The plant has then been tested successfully in a solar cooling system. It includes an automatic control unit mastering all internal functions, such as start-up and stop routines and protection against crystallisation and freezing. Due to the application of a speed controlled mechanical solution pump efficient part load operation is achieved.

A second prototype of the chiller will be integrated in a solar thermal system in summer 2003 and will be demonstrated in the field until 2004. The solar thermal system, cooling tower and chilled ceiling panels are installed at present and will be ready for operation in June 2003. A simulation tool for solar cooling applications has been developed and a transient simulation parameter study has been carried out with the aspect of user-comfort being the focal point.

4 NOMENCLATURE

COP	Coefficient of performance	(-)	EH	exceeding hours	(h)
f	specific solution circulation ratio	(-)	**Subscripts**		
n	number of tubes	(-)	H	height	
? T	temperature difference	(K)	log	logarithmic	
UA	heat transfer rate	(W/K)			

5 ACKNOWLEDGEMENTS

The prototype development project has been supported by European founding within the Joule programme (contract No. JOR3 CT97 0181). The current plant development is supported by the European Union and the city senate of Berlin within the UEP-programme (contract. No. 10530 UEP OÜ2).

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RÉFRIGÉRATEUR À ABSORPTION DE PETITE TAILLE AVEC EAU/LI-BR COMME FLUIDE ACTIF POUR LA RÉFRIGÉRATION SOLAIRE ET L'UTILISATION DE LA CHALEUR COGÉNÉRÉE POUR LA RÉFRIGÉRATION

RESUME : Ces derniers temps, on observe une croissance de la demande en réfrigérateurs à absorption de petite taille pour la réfrigération solaire et la trigénération, c'est-à-dire l'utilisation de la chaleur cogénérée pour la réfrigération. Jusqu'à aujourd'hui, il était impossible de se procurer des réfrigérateurs de moins de 35 kW. Suite à un projet européen commun, un producteur et distributeur allemand de systèmes thermiques solaires a récemment démarré le prototypage d'un réfrigérateur à absorption de 10 kW avec eau/LiBr comme fluide actif. La machine nécessite une circulation d'eau chaude de 80 à 100 °C et présente une performance optimisée par rapport aux machines standards actuelles. Une conception de cycle prudente et un contrôle entièrement automatisé permettent d'obtenir une charge partielle rentable avec 30% de charge. Mettant le cap sur une configuration et un contrôle de système optimaux, une simulation transitoire de système a été réalisée à l'avance. Les données opérationnelles rassemblées au cours de la phase de lancement seront présentées. D'autres essais effectués dans des conditions réelles avec des capteurs plats pour faire circuler la source de chaleur seront menés dans une installation de réfrigération solaire d'un immeuble de bureaux à Berlin. Un essai sur le terrain à grande échelle est en préparation.
Mots-clés : réfrigérateur à absorption, réfrigération solaire, trigénération, analyse des cycles, échangeur de chaleur, prototype, essai, simulation transitoire